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# GEOLOGICAL MAPPING IN VOLCANIC REGIONS: ICELAND AS AN EXAMPLE

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**ABSTRACT**

This paper reviews the approach to geological mapping of low and high temperature geothermal areas in Iceland. Geological mapping is a key part of the surface exploration of geothermal areas before the subsurface is explored through drilling. The objectives of geological mapping are manifold but focus on outlining the geological setting and structure of the area; identifying fractures and fissures, which are controlling fluid flow in the system; outlining the potential size of the system and characterising the size, age and productivity of the heat source etc. The outcome of geological mapping is presented on maps. Geothermal maps show the distribution of the different types of geothermal manifestations in comparison with volcanic and tectonic structures, while the geological map presents the type of volcanic deposits and their extent, age relationship and possible origin. Along with geochemical and geophysical surface exploration, this constitutes the basis for siting the first wells and proceeding to the subsurface exploration phase, providing the outcome of surface exploration is promising.

Iceland is located in an extensional geological setting straddling the North Atlantic mid-ocean ridge. The neo-volcanic zone extends from the southwest to the northeast of the country, which constitutes parallel aligned volcanic systems within which the high temperature geothermal areas are located. This paper presents some of the volcanic and tectonic features characteristic of geothermal systems in Iceland.

## 1. INTRODUCTION

The process of developing geothermal fields for utilisation can be divided into three stages; surface exploration, exploration drilling and development drilling. The surface exploration stage is usually implemented in three phases starting from (1) a due diligence work which is carried out by thoroughly reviewing available information related to previous investigations of hot springs, fumaroles, silica mounds, solfataras and alteration zones as well as air-photo analyses and remote sensing studies, (2) field reconnaissance surveys including the acquisition of geology and geochemistry data and a review of the environmental aspects of the area and 3) detailed exploration survey, which includes geological mapping, geophysical surveying and geochemical sampling and analysis.

The objective of the surface exploration is to obtain information about factors such as; 1) the geological setting, 2) structural and hydrological setting within the system, 3) the size of the system, 4) subsurface temperatures and 5) heat source and natural recharge. The results of the different surface investigations are combined into a preliminary conceptual model of the system and are used to outline suitable sites for exploration drilling (Richter et al., 2010; Pálmason, 2005; Steingrímsson & Guðmundsson, 2010). Thus geological mapping features most prominently in the early stages of exploration and development of a geothermal system, but the geological and structural framework that is delineated during this stage, forms the basis of the subsequent drilling stage.

## 2. GEOLOGICAL MAPPING

Geological or geothermal mapping is applied both on a regional scale, e.g. in country-wide reconnaissance for areas with geothermal potential, as well as on a local scale when exploring specific geothermal areas.

### 2.1 Regional reconnaissance

Regional or country-wide geothermal reconnaissance aims to identify areas with geothermal potential, thus the geologist is required to cover large areas in a relatively short time. In such regional surveying the geologist is seeking to locate and map areas with geothermal manifestations such as warm springs, hot springs, fumaroles, hot and altered ground, but temperature, flow rate, pH and conductivity of the spring is recorded and samples collected for geochemical analysis. In order to find hidden or partly hidden geothermal areas the geologists commonly use a number of different approaches depending on availability; review of regional geological maps, aerial photos, remote sensing such as thermal imaging, while place names can often point to locations with warm or hot springs, e.g. in older literature. When the geologist is eventually in the field it is often valuable talking to local farmers, as they are most likely to know about less conspicuous geothermal manifestations, springs and fumaroles.

The preliminary geothermal reconnaissance is used to rank the geothermal areas according to their estimated potential, that is to say preliminary information about potential size and estimated reservoir temperature. This preliminary work forms the foundation for governments to either pursue the exploration of the geothermal fields under governmental administration, or to lease the exploration rights of the geothermal field to private companies through open tendering.

### 2.2 Geological mapping of geothermal areas

Geological mapping is more detailed during exploration of a specific geothermal area; however, the detail required in the mapping depends on the type of geothermal area and the costs of carrying it out. In Iceland geothermal energy is abundant with numerous low and high temperature geothermal fields. Many low temperature fields have been successfully developed for domestic heating while the high temperature fields have both been developed to sustain both power generation as well as serving for direct use purposes, e.g. domestic heating.

Approximately 25-40 high temperature fields straddle the neo-volcanic zone, which extends from the south-western corner of the Reykjanes peninsula, across the central highland and to the north-eastern shores of Iceland (Figure 1), but the neo-volcanic zone forms the landward extension of the North Atlantic mid-ocean ridge. The low temperature areas are found all across the country both inside and outside the neo-volcanic zone, although they are more predominant in the western part of Iceland. The low temperature geothermal fields are used for domestic heating, green house heating and fish farming etc.

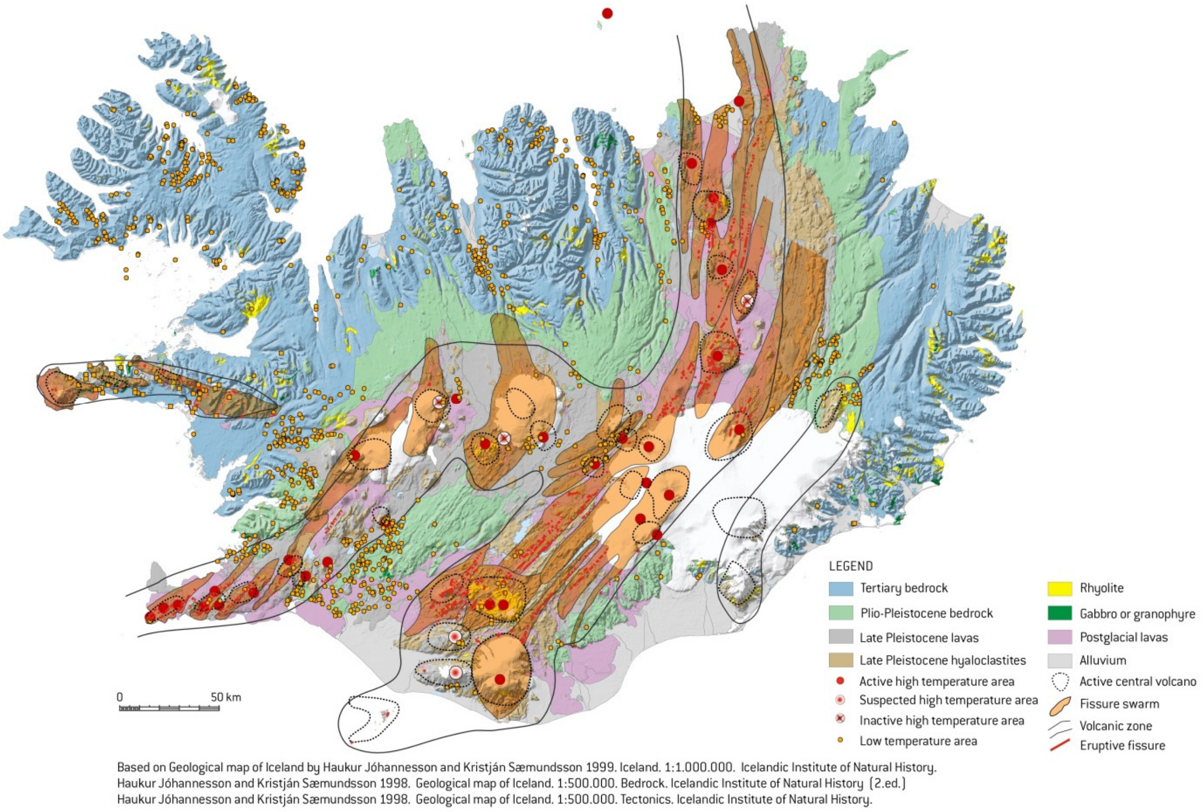


FIGURE 1: Geological map of Iceland highlighting the volcanic systems and central volcanoes within the neo-volcanic zone (Jóhannesson and Sæmundsson, 1998)

### 2.3 Geological mapping in low temperature areas

Exploration of low temperature geothermal areas has to be cost efficient to ensure that the energy source is competitive with other conventional energy sources. Geological mapping is therefore more limited and the primary objective is to identify the main permeable fractures and the centre of warm water upflow. In Iceland low temperature fields located outside the neo-volcanic zones are situated in the Tertiary volcanic pile (Figure 1), which formed more than 3 million years ago, but in these formations the porosity is limited, thus aquifers are mostly linked to dykes or active faults, which remain open and allow up-flow of warm water to the surface (Figure 2).

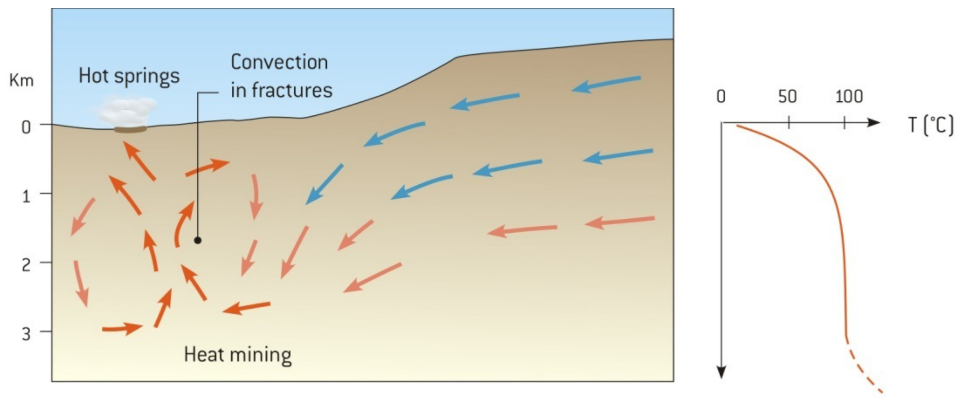


FIGURE 2: Conceptual model of low temperature geothermal systems in Iceland. Deep circulation along dykes and active faults allows the groundwater to heat and rise to the surface in the upflow zone of the convection cells (Axelsson, 2008). The diagram to the right shows a typical geothermal gradient in a low temperature geothermal reservoir characterised by fracture bound convection

The aim of geological mapping in low temperature fields is to find where the centre of warm water upflow is located by identifying, for example, faults and dykes and to determine the strike and dip of the permeable structures in order to outline an appropriate well site, which will intersect the structures at depth.

Geological mapping in low temperature areas typically includes:

1) Detailed mapping of warm and cold water springs, measurement of their temperature, flow rate, pH and conductivity.
2) Temperature measurements in soils, where they cover the basement rock.
3) Detailed mapping of all visible fractures, faults and dykes in the vicinity of the expected drilling area, including determining strike and dip of the structures.
4) Temperature measurements in shallow holes to determine the temperature gradient near the surface. In Iceland this method has been successfully applied to identify thermal anomalies
5) In some cases geological mapping is complemented by geophysical surveys in areas with limited surface exposure, however magnetic surveys are used to discern dykes, and in rare cases, faults. Resistivity profiling is a rather expensive method and thus is used sparingly, although it is applied to delineate fluid conductive fractures.

Providing that the geological investigations point towards the presence of a low temperature field, they can form the foundation for siting a well in preparation for the next stage of the exploration of the field.

### 2.4 Geological mapping in high temperature areas

Geological mapping in high temperature areas is much more extensive. Mapping during the surface exploration phase generally involves the following:

- Detailed geological map of the geothermal field and its surroundings
  - Rock type
  - Frequency, volume and type of volcanic eruptions
- Detailed mapping of tectonic features such as faults, fissures and fractures
- Mapping of thermal manifestations, including recording the temperature, flow rate, pH, conductivity etc.
- Detailed mapping of surface alteration and alteration minerals
- Thermal manifestations of tectonic features and volcanism – heat sources, hydrology and flow paths in the reservoir
- Mapping of groundwater, cold springs, lake levels and groundwater levels
- Risk assessment
- Environmental aspects

The basic concept of geological mapping is to present the stratigraphy, rock types and structural features of the exploration area. Geological mapping in geothermal exploration focuses in particular on establishing the volcanic history of the area; the type of volcanic eruptions and their tectonic setting, the volume of the eruptions, their frequency and changes in volcanic and tectonic activity through time. Volcanic activity and type of rocks erupted can shed a first light on the geological conditions within the geothermal reservoir and the size and configuration of its heat source.

Structural mapping is an integral part of studying volcanic systems, but through this work, structural features are outlined, and both large and small scale structures such as faults and fractures are mapped. At first they can be outlined with the aid of satellite images and aerial photos, followed by field work, but mapping includes determining the movement and amount of displacement along the faults (normal/reverse/strike-slip/oblique), so that the stress regime and orientation can be determined. The aim is to make preliminary projections about the orientation of fluid conductive faults and fractures with depth, being both volcanically and tectonically controlled.

Through mapping it is also attempted to date larger tectonic events and the frequency of their occurrence through geological correlation, tephrachronology and/or $C^{14}$ dating. Current tectonic activity and crustal movement can be monitored through an array of geophysical techniques such as GPS-networks and InSAR satellite techniques and seismic surveys.

Geological mapping shows not only a first inference about the geology and structural setting within the geothermal reservoir but also gathers evidence about the location, size and frequency of volcanic and tectonic events and possible slope failures. When developing geothermal fields, these data are used to evaluate the probability of such hazards, to minimize the risk of damage to surface constructions, in particular to the power plants.

### 2.5 Geological and structural mapping in geothermal areas in Iceland

Iceland is located on the Mid-Atlantic Ridge, which is an active spreading centre, where the American and Eurasian plates are moving apart at a rate of 2 cm/yr. In Iceland the region of extension and volcanism is centred within the neovolcanic zone, which extends across the country from the south-western corner to the northeast (Figure 1). A mantle plume is located under the south eastern part of Iceland, resulting in increased magmatic production rate and the sub-aerial exposure of Iceland.

The volcanic activity is centred within the neovolcanic zone of Iceland, but the volcanic activity is constrained by volcanic systems arranged in an en echelon pattern (Figure 1). The volcanic systems comprise a fissure swarm, a central volcano and a high temperature geothermal area, but the high temperature geothermal areas are all located within the Icelandic neovolcanic zone.

The rocks in Iceland are fairly uniform in composition with more than 90% of the rocks being of basaltic composition. The onset of glaciations 3 million years ago in the Plio-Pleistocene was the result of general cooling of the Northern Hemisphere. This transformed the Icelandic landscape as it became covered with glaciers and sub-glacial volcanic eruptions created hyaloclastite ridges and table mountains. As a result of this climatic change, in many of the high temperature areas hyaloclastites commonly form the cap rock of the geothermal reservoirs, while basaltic lavas and pillow basalts are the principal reservoir rocks.

The maximum volcanic production rate is in the central volcanoes of the volcanic systems, which therefore constitute the topographic highs along the fissure swarms. The distribution and volume of volcanic products erupted on the surface provide clues about the dynamic interaction between volcanism and tectonics. Just as importantly this provides information about the configuration of the magma plumbing system and the rate of magmatic input into the shallower part of the crust. The cooling and solidifying magma in the form of plutons, dyke swarms and sills form the heat source of the geothermal systems. As only a percentage of the magmatic input into the shallow crust is erupted onto the surface, estimating the volume and distribution and production rate of volcanic deposits through time provide essential information about the potential depth, shape, size and age of the heat source for the geothermal system.

To determine the age of volcanic deposits a combination of cross correlation of deposits and structures is applied along with dating of selected samples, this being K-Ar, Ar-Ar dating or $C^{14}$ dating depending on the age of the deposit. Deposits from the Holocene have been successfully dated in Iceland using tephrachronology, but the record of larger volcanic eruptions is preserved as ash layers in soils across the country.

## 2.6 Krafla volcanic system

Development of central volcanoes in Iceland can be divided into several stages, but they form at the centre of highest volcanic production rate within the volcanic systems. As an example, the Krafla central volcano in north-eastern Iceland is briefly described here based on some of the following references: Sæmundsson (1991, 2008a,b), Ármannsson et al. (1986); Mortensen et al. (2009).

The oldest rocks related to Krafla central volcano are at least 300.000 years old, but over this time a large basaltic shield has developed, which constitutes the Krafla central volcano. The shield is about 20 km in diameter with a 300-400 m high relief. In the centre of the volcano is an 8x10 km large caldera (Figure 3). The caldera formed as a result of a large paroxysmal eruption approximately 110.000 years ago, which created an extensive ignimbrite deposit that is most prominent east of the caldera. Today the caldera has an elliptical shape as a result of the continued extension along the rift zone. The caldera has almost been filled with hyaloclastites and basaltic lavas during succeeding eruptions. Within the caldera is a large east-west trending area with geothermal manifestations (Figure 4), but the geothermal manifestations are most active and prominent east of the centre of the caldera, while they have cooled and/or are extinct towards the edges of the caldera. The caldera is intersected by a 90 km long, almost N-S striking fissure swarm (N5-10°E). The fissure swarm is 7-8 km wide at the central volcano and divides into two southwards from the caldera.

In the Holocene volcanic activity have been shifting back and forth between the two sections of the fissure swarm, but fissure eruptions have been originating from the eastern section of the swarm in the past 3000 years at intervals between 300-1000 years. The volcanic eruptions have occurred along both linear and curved fissures. Eruptions along curved fissures are conspicuous in the north-eastern part of the caldera as well as outside the caldera, but these curved fissures form the surface manifestations of cone sheets, which are believed to originate from a shallow magma chamber beneath the caldera. The linear fissure eruptions extend towards the north and south along the fissure swarm, but they also originate from the centre of the caldera were maximum extension has taken place, as exemplified with the latest volcanic episode, the 1975-1984 Krafla Fires. In addition to the geological features at surface, monitoring of crustal deformation and seismicity during the Krafla Fires supported the notion of magma accumulation in a shallow magma between 3-7 km depth below the Krafla caldera (Einarsson, 1991) and subsequent extrusion of lava onto the surface along the N-S fissure swarm, when the critical pressure in the magma chamber was exceeded.

It is not only basaltic lava, which is extruded from the Krafla Central Volcano. Both rhyolitic and mixed extrusives (rhyolite/basalt mixture) form prominent ridges outside the caldera and along N-S fissures in the eastern part of the caldera (Figure 3), but the geochemistry of rhyolites suggest that they have formed by partial melting of hydrothermally altered basalt in the vicinity of the magma chamber. In the eastern part of the caldera are other distinct volcanic features in the form of explosion craters (Figure 4). No significant magma extrusion has been connected to these craters, which are 300-400 m in diameter, but it is suspected that steam explosions from the underlying high temperature geothermal system have played a significant role during their creation.

The geological studies of Krafla geothermal area have thus shown that it formed in an active volcanic setting, where frequent volcanic eruptions ensure a high magmatic input into shallow crustal levels with a magma chamber at 3-7 km. In the eastern part of the caldera there is a correlation between the presence of the hottest, most active and pervasive part of the geothermal surface manifestations and recent volcanism in the caldera. This includes fissure eruptions and explosion craters as well as the most recent extrusion of rhyolite merging towards the current centre of the magmatic heat source, which supports the heat for a high temperature geothermal reservoir.


FIGURE 3: Geological map of Krafla. Holocene lavas (purple and pink colours) and hyaloclastite ridges (brown colours) have filled the caldera centre. Yellow colours represent rhyolitic and mixed rhyolite/basalt deposits, which are conspicuous outside the caldera, while the most recent deposit is in the eastern part of the caldera (Sæmundsson, 2008a). Map scale is 1:25000. The width of the map is equivalent to ~12 km

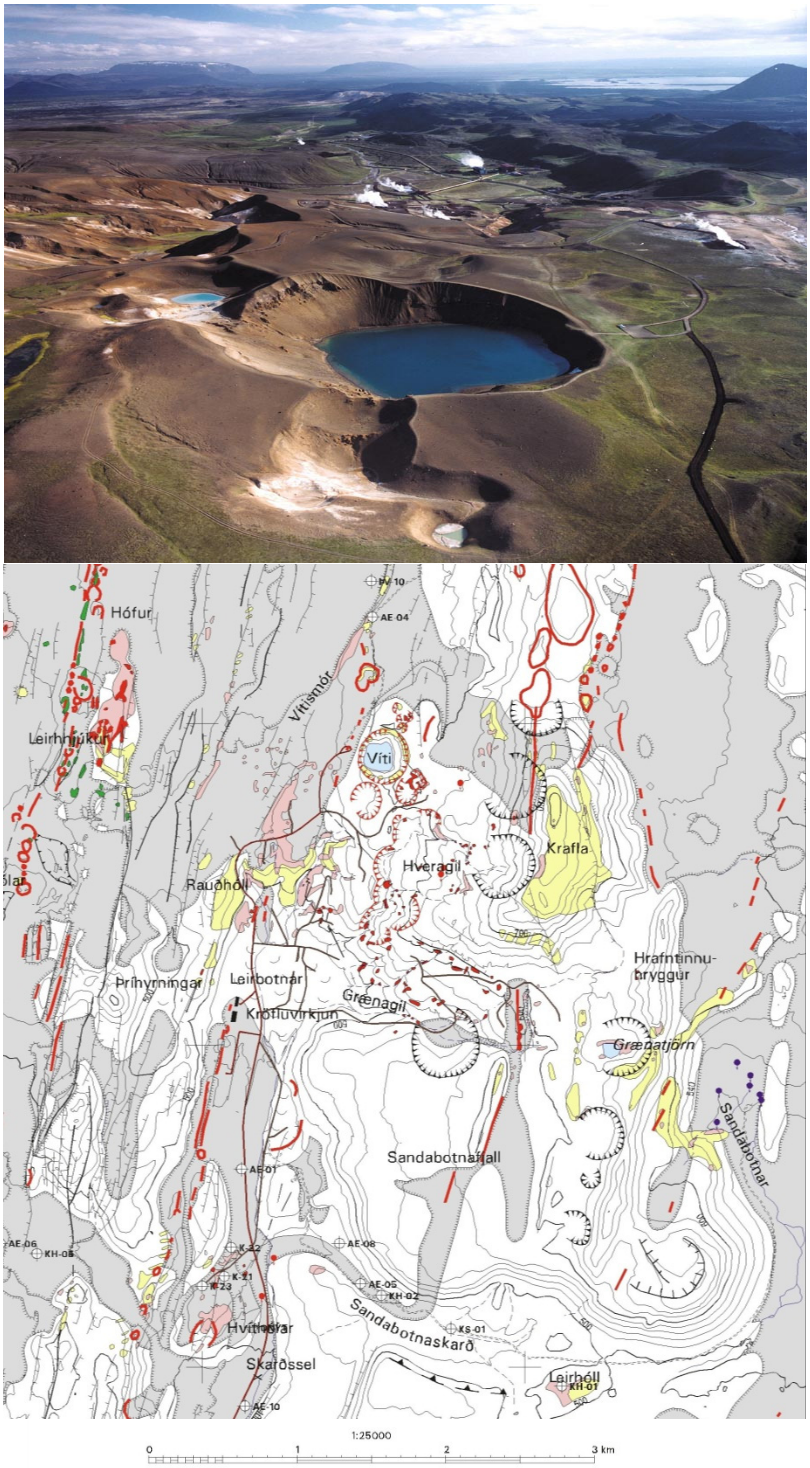


FIGURE 4: Above: Photo looking towards the south from Krafla with explosion craters in the foreground (Picture: Á. Guðmundsson) Below: Geothermal map from part of Krafla geothermal area, outlining the location of explosion craters (circular features), fumaroles (red dots), hot ground (pink) and slightly altered ground (yellow). Serrated lines indicate normal faults while lines with triangles symbolize the caldera margin (bottom) (Sæmundsson, 2008b)

## 3. GEOTHERMAL MAPPING

Mapping geothermal manifestations in high temperature areas in Iceland is relatively easy due to sparse vegetation (Figure 5). Aerial photos or satellite images can be used to initially outline the aerial distribution of the geothermal manifestations, but this has to be complemented by field work for detailed mapping. In the field the aerial distribution and directional trends of the geothermal manifestations are mapped along with their intensity, coherence, type of geothermal manifestations (e.g. fumaroles, solfatara, hot and boiling springs, mud pools, steaming ground, hot ground) and identification of what type of precipitates have formed there (e.g. sulphur, silica, aragonite, hematite and clay types). At times XRD-analyses are used to identify the type of precipitates. Both active and extinct geothermal manifestations are mapped, but through correlation with surrounding lavas and soils, it is attempted to establish when the geothermal manifestations became extinct. The outcome of the field work is a geothermal map showing the extent and type of geothermal manifestations in correlation with the structural features (Figure 5). In Iceland it is common that geothermal manifestations appear along faults and fissures as is exemplified in the geothermal map from Þeistareykir geothermal area in NE-Iceland (Sæmundsson, 2007), which reflects that fluid flow in the geothermal system is to a large degree controlled by tectonics.

When mapping active geothermal manifestations, temperature, flow rate, pH and conductivity is measured and fluid and gas samples collected for geochemical analyses. In areas covered with thick soils a complimentary temperature survey may be carried out, but the density of measurements is dependent on the survey area. Figure 6 shows an example of a temperature survey conducted at the Reykjanes geothermal area in SW Iceland. This reveals a rather complex set of lineaments, but from the map N-S, NW-SE and NE-SW lineaments in the temperature distribution happen to correlate with the orientation of open fissures, faults and eruptive fissures within the Reykjanes field. Based on the temperature distribution map the thermal output from the geothermal field can be estimated. Therefore s maps of this kind can give a first idea of the potential of such a field.

The ground usually becomes covered with snow during the winter in Iceland. In the geothermal areas melting of snow is also used as a tool to map the aerial extent of the active geothermal manifestations, and repetition of these measurements over several years can outline changes in the geothermal surface activity. Such monitoring can reveal natural changes through time, which can be linked to deeper seated changes in the geothermal reservoir e.g. cooling or volcanic episode, or may reflect changes as a response to production from the geothermal field.

Mapping diffuse $CO_2$ degassing through soil is another useful method to delineate areas with fractures controlling flow in the geothermal systems. This type of mapping has been successful in revealing anomalies in the $CO_2$ flux that align along already known faults and fractures, but it is has also revealed active fractures that are not visible at surface. Wells have been directed through these anomalies in Iceland, and the outcome have been highly productive wells, reinforcing the correlation between high $CO_2$ soil fluxes and active flow controlling fractures in the reservoir (Ármannsson *et al.*, 2007). Maps of $CO_2$ soil flux and snow melt are thus far not part of the initial surface exploration stage in Iceland, but are rather included in the later stages of field development, e.g. as part of environmental monitoring of changes in the geothermal areas.

The geothermal map helps to develop the first conceptual model of the geothermal field. The aerial distribution of the geothermal manifestations gives the first indication of the potential size and capacity the geothermal reservoir. Variation in the type of geothermal manifestations that occur across the area can outline zones of upflow and/or out flow and likely temperature regime in the reservoir.
Geothermal manifestations such as fumaroles, boiling springs, hot spring and mud pools and deposits of native sulphur and siliceous sinter deposits are typically found above upflow zones from high temperature geothermal reservoirs. If leached rocks and acid springs are present this could even point towards a vapour dominated reservoir, but gasses from these reservoirs condense near surface to form acids. Areas with $CO_2$ springs and travertine deposits (aragonite/calcite) form either in vicinity of relative low temperature reservoirs which are only suitable for direct use purposes, or alternatively mark the outflow zones from hot geothermal reservoirs where travertine deposits form through cooling and groundwater dilution of the fluids (Goff and Shevenell, 1987).

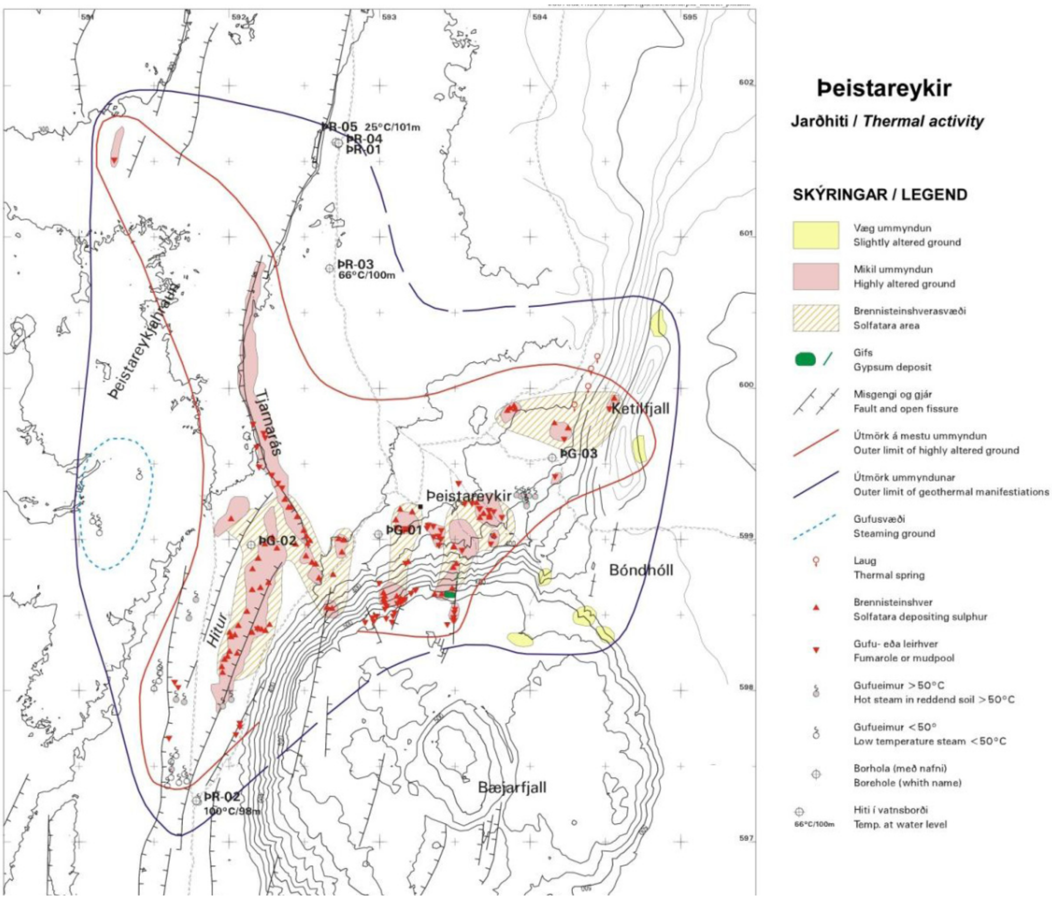


FIGURE 5. Geothermal map of Þeistareykir Geothermal field NE-Iceland. Faults and fissures are shown, and the geothermal manifestations appear along the faults and fissures (Sæmundsson, 2007)

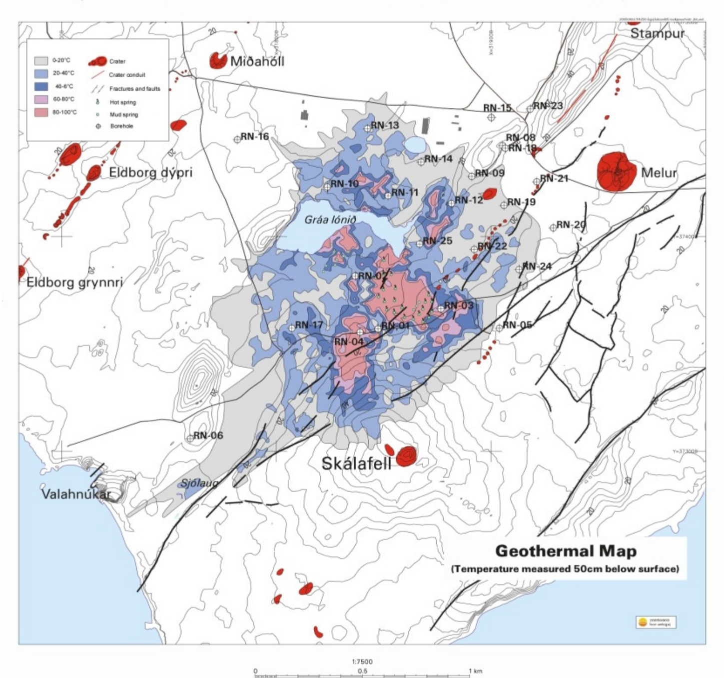


FIGURE 6. Temperature distribution map from 1968 of the Reykjanes geothermal area SW-Iceland. Temperature was measured at 50 cm depth in soil (Jónasson 1968)

## 4. SIMPLE CONCEPTUAL MODEL

After surface exploration of geothermal areas, the outcome of geological mapping, geochemical and geophysical surveying are combined to form the basis for developing the first conceptual model of the geothermal system. This paper has focussed on the information gathered through geological mapping, while other papers will present the principles and interpretation of geochemical and geophysical surveys.

The objective of the conceptual model is to outline the potential target areas for the first exploration well/s, where the upflow zone is located and the highest temperatures are expected to be found. The model should highlight potential structures, which control the fluid flow in the reservoir and their orientation with depth in order to outline drilling targets.

In Figure 7 is an example of a simplified conceptual model, which is representative of high temperature systems in Iceland, but arrows are used to represent the fluid cycle within such systems. Through surface exploration the detail of such a model increases and it is possible to start highlighting the potential size of the geothermal area, outline potential upflow and recharge centres, fluid conducting structures, likely reservoir formations and heat source characteristics.

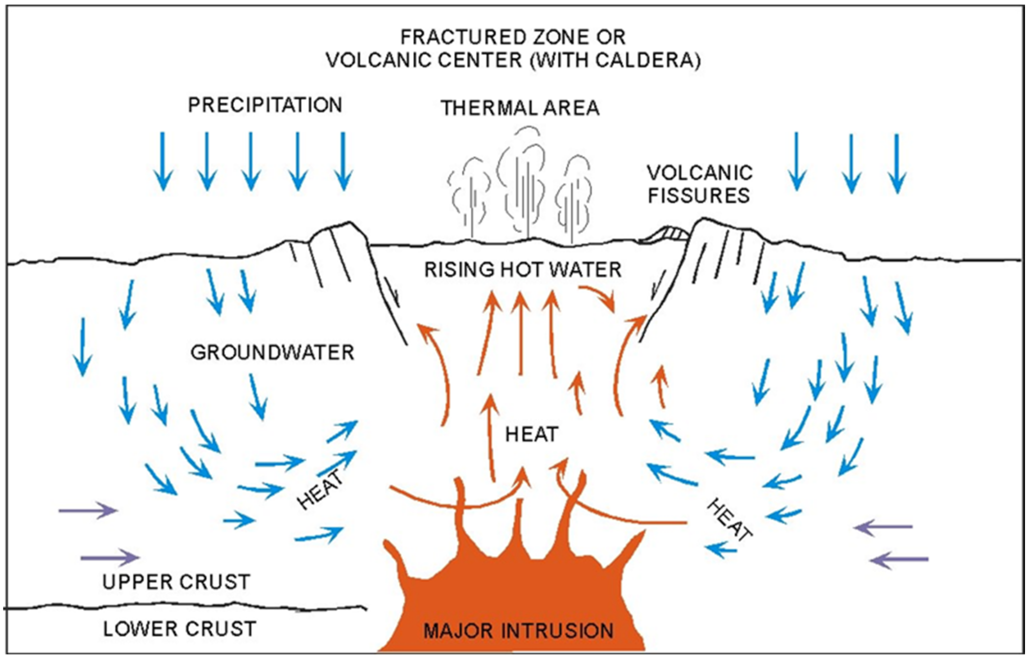


FIGURE 7. Simplified conceptual model of a magmatic heated high temperature geothermal system in a region of rather low relief, e.g. region of extension as in Iceland (Axelsson, 2008)

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